

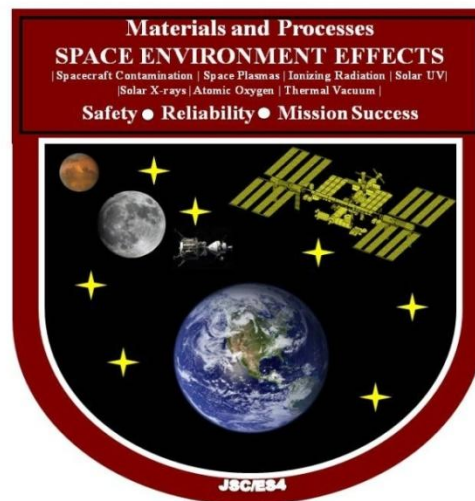
# ***Space Radiation Effects on Spacecraft Materials and Avionics Systems:***

***No epic challenge here, but ignoring this can lead to loss of  
mission and spacecraft***

**NASA/MIT Workshop**

**06/26/12**

**NASA/JSC/ES4/Steve Koontz**



# ***Presentation Outline***

- ***Effects of Space Radiation on Exposed Spacecraft Materials***
  - ◆ ***Space Radiation Dose to Exposed Spacecraft materials: Dose vs. Depth on the Exterior of the Spacecraft***
  - ◆ ***Some General Considerations: Plastics and Polymers in the Space Radiation Environment***
  - ◆ ***Plastics, Polymers, Adhesives (and Hydrazine)***
  - ◆ ***Carbon fiber composites***
  - ◆ ***Ceramics and glasses***
  - ◆ ***Lubricants***
- ***Effects of Space Radiation on Spacecraft Electronic Systems***
  - ◆ ***Total Ionizing Dose***
  - ◆ ***Displacement Dose Damage***
  - ◆ ***Single Event Effects***
  - ◆ ***Photovoltaic Systems***
  - ◆ ***Guidance Navigation, Control, Data Handling***
- ***What do I do about all this?***
- ***And what happens if I don't?***
- ***References***



*Photograph of Hubble Space telescope taken during the second servicing mission, showing the very large, vertical light shield cracked area and the tightly curled upper light shield cracked area. Credit: NASA*



*Hubble during Servicing Mission 3B in 2002 with New Outer Blanket Layers. New Outer Blanket Layer covers were installed on Bays 5 (not pictured), 7 and 8 during Servicing Mission 4. Credit: NASA*

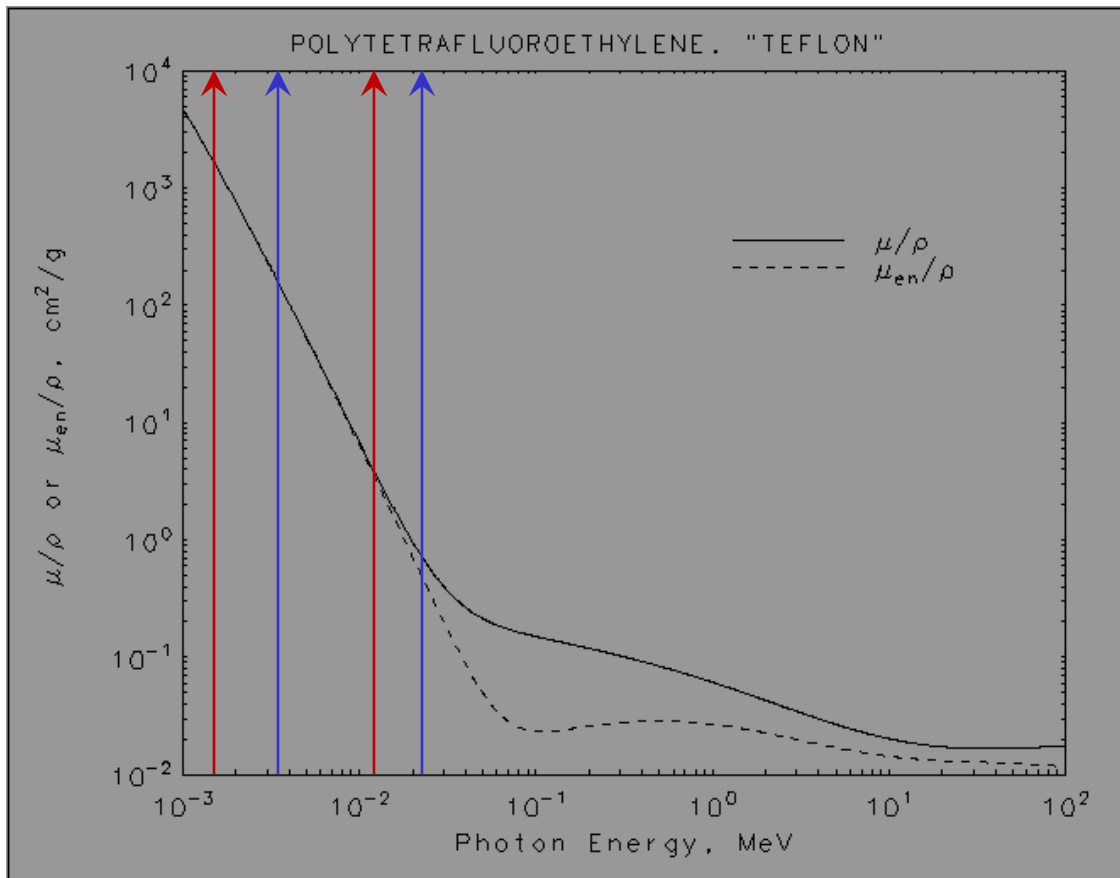
## ***Effects on Exposed Spacecraft Materials***



***ISS – No external Teflon materials failures in 12 years (including the mobile transporter cable)**  
Credit: NASA*

# ***Space Radiation Dose to Exposed Spacecraft Materials: Dose vs. Depth on the Exterior of the Spacecraft***

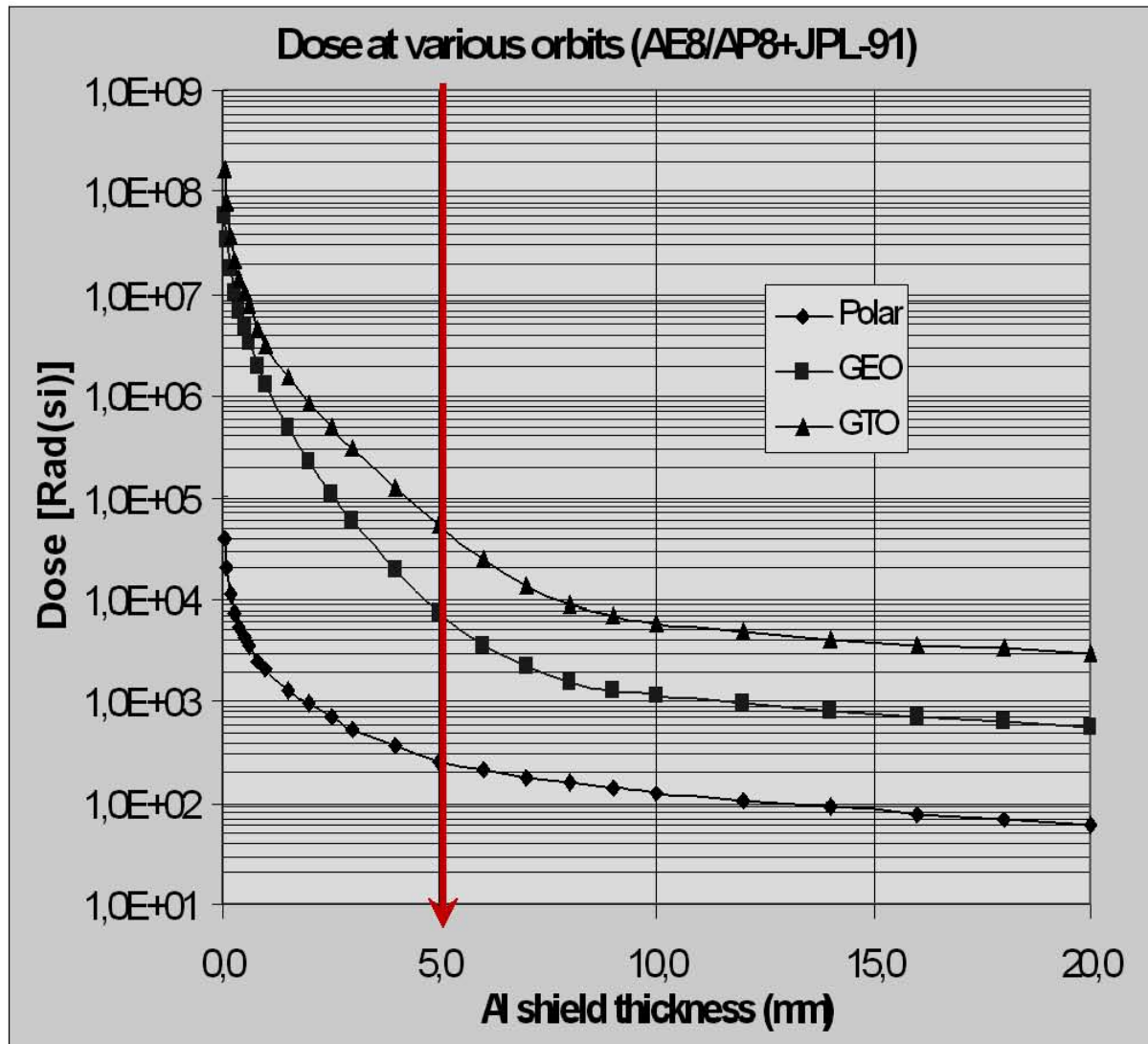
*Energetic photons and the low-energy end of the charged particle populations drive the near surface dose rate and materials degradation*



***The poly tetrafluoroethylene (PTFE) Teflon soft X-ray mass adsorption coefficient is typical of many organic materials and changes by several orders of magnitude as photon energy increases from  $10^{-3}$  to  $10^{-1}$  MeV.***

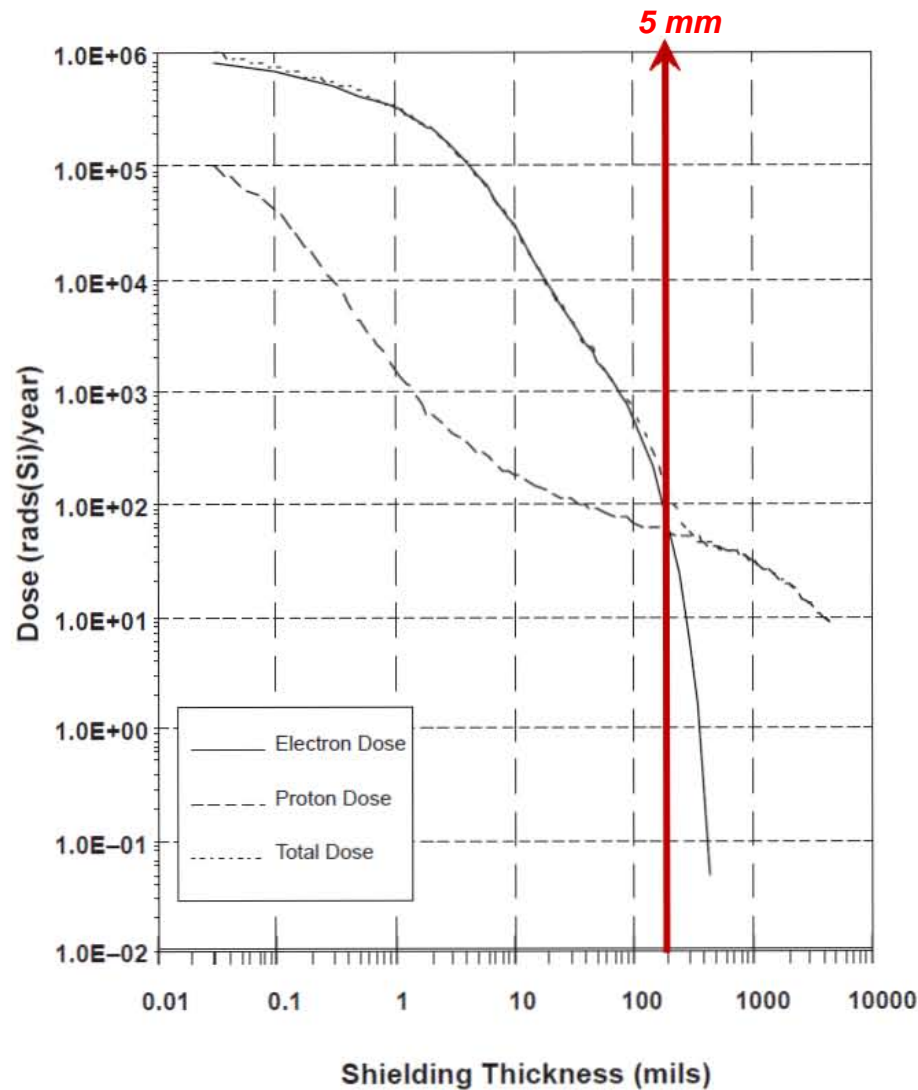
***Given the range of soft X-ray energies in each of the two bands (red and blue vertical lines) reported by the geosynchronous orbiting environmental satellite (GOES), and the rapidly changing mass absorption coefficient over the energy range of interest, estimation of surface dose is accompanied by considerable uncertainty.***

# ***Van Allen Belts – Annual Dose vs. Altitude/Orbit - Al Shielding Mass - Trapped Radiation (electrons and protons)***



Credit: ESA/Spennis

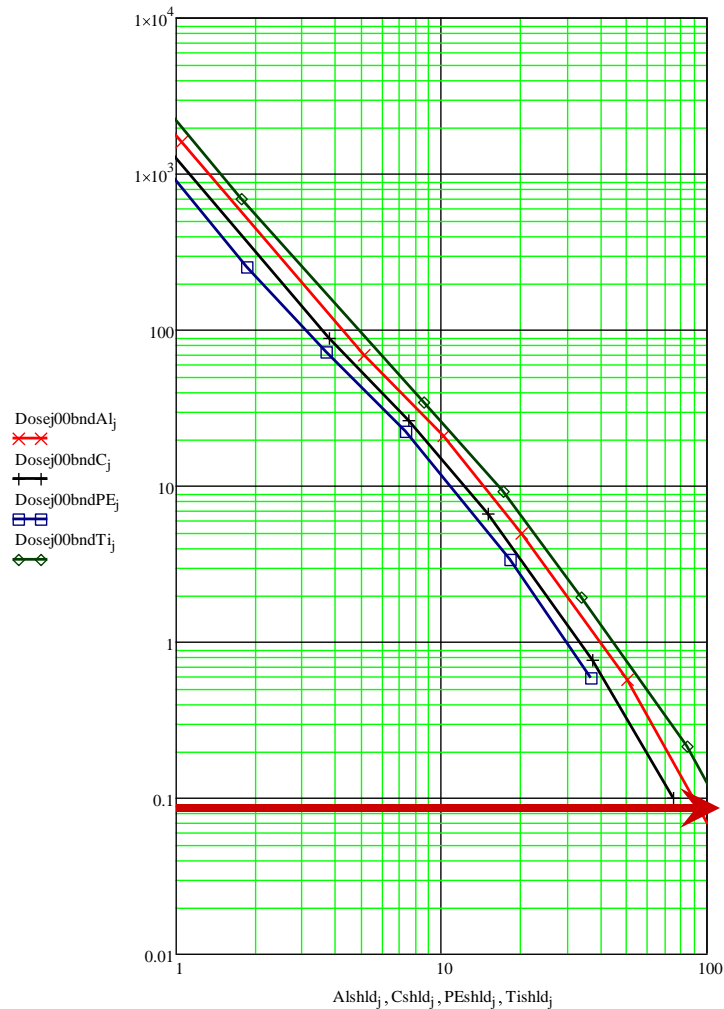




***ISS Design Environment - electron and proton dose to the center of an aluminum sphere of radius = shielding thickness in mils (1 mil = 0.025 mm)***

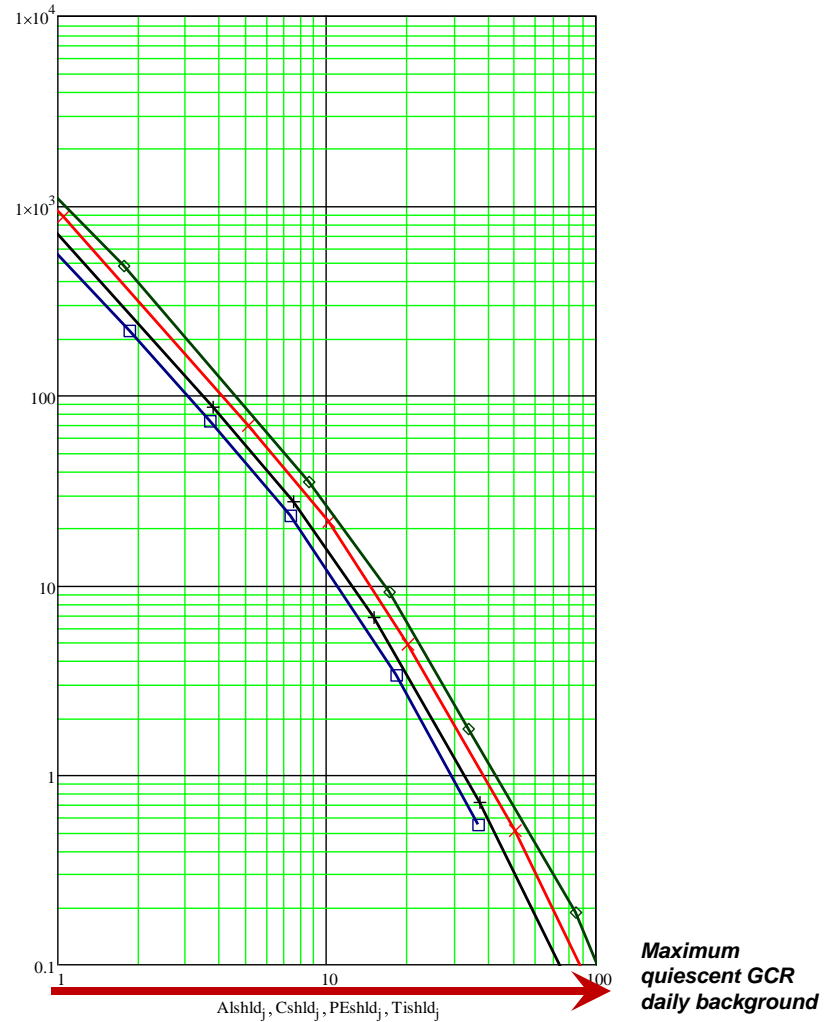
# FLUKA: Solar Particle Events – Dose, Depth, Shielding Material

Steve Koontz, William Atwell, Brandon Reddell, Kristina Rojdev; NASA TP-2010-216133



**July 2000 SPE**

*Maximum quiescent  
GCR daily  
background*

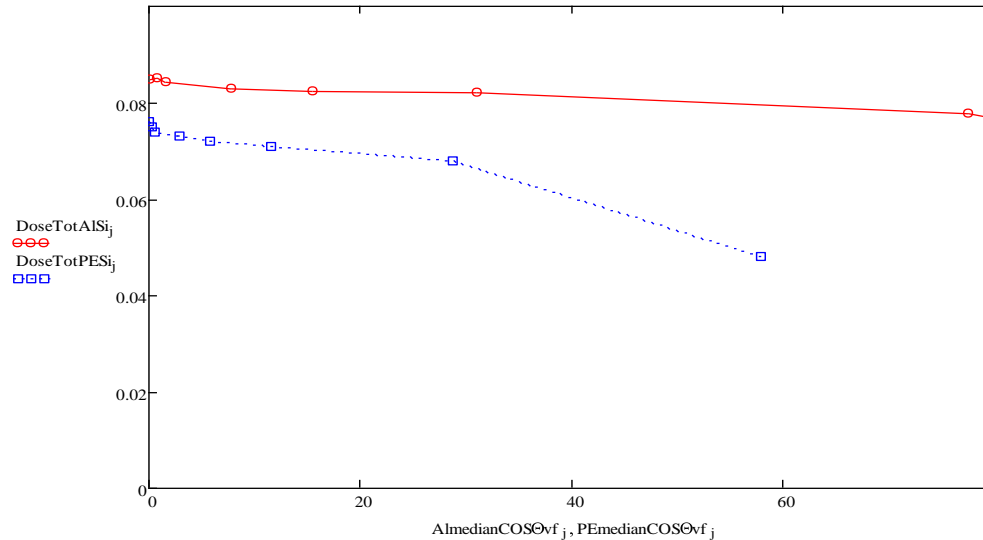


**October 2003 SPE**

*Maximum  
quiescent GCR  
daily background*

### 3.4 FLUKA: Effects of spacecraft shielding mass elemental composition/ atomic number (Al vs. PE) on the spacecraft SEE environment (GEO/Interplanetary)

Shielding mass Z effects; Al vs. PE shielding mass; TID (cGy/day) to Si shells

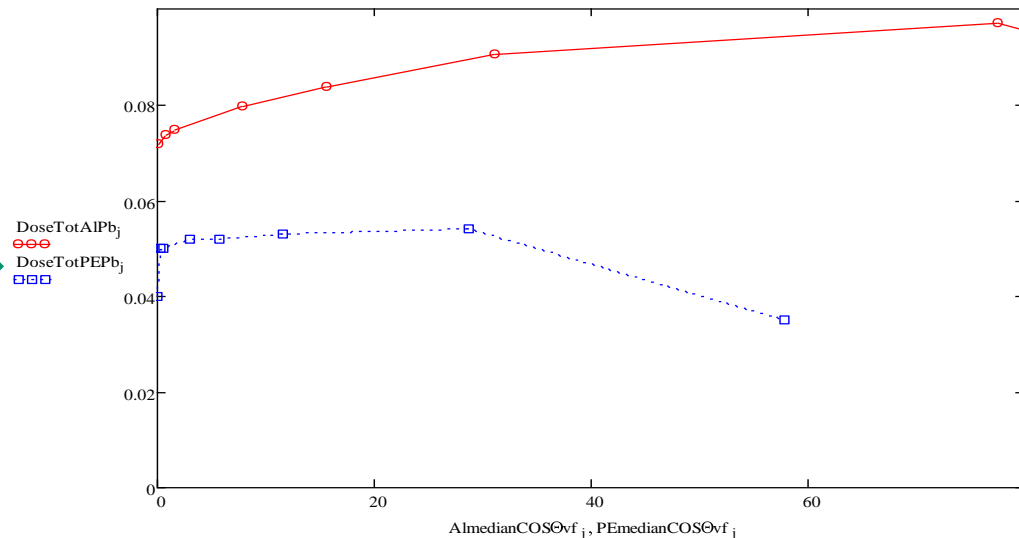


Total ionizing dose (TID) in cGy (Si) to the 10 $\mu$  Si shells (with 1 $\mu$  Pb over layers) for both **Al** (*DoseTotAlSi*) and **PE** (*DoseTotPESi*) shielding. TID (y axis) vs. median shielding mass (x axis)

Total ionizing dose (TID) in cGy (Pb) to the 10 $\mu$  Si shells (with 1 $\mu$  Pb over layers) for both **Al** (*DoseTotAlSi*) and **PE** (*DoseTotPESi*) shielding. TID (y axis) vs. median shielding mass (x axis)



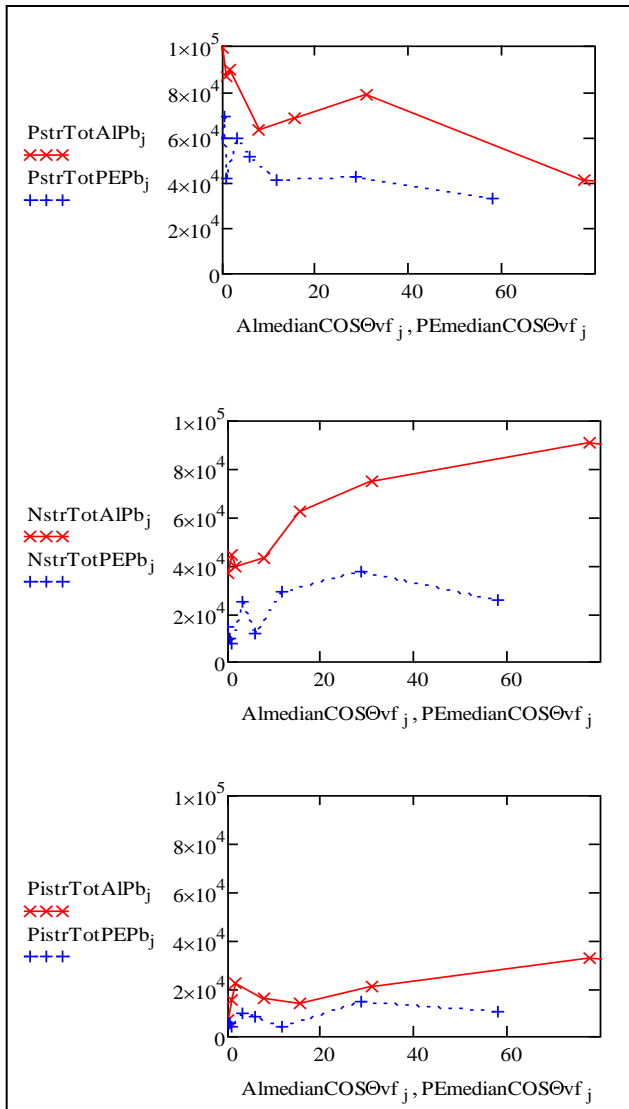
Shielding mass Z effects; Al vs. PE shielding mass; TID (cGy/day) to Pb shells





### 3.5 FLUKA: Effects of spacecraft shielding mass elemental composition/ atomic number (Al vs. PE) on the spacecraft SEE environment (GEO/Interplanetary)

**Pb shells**

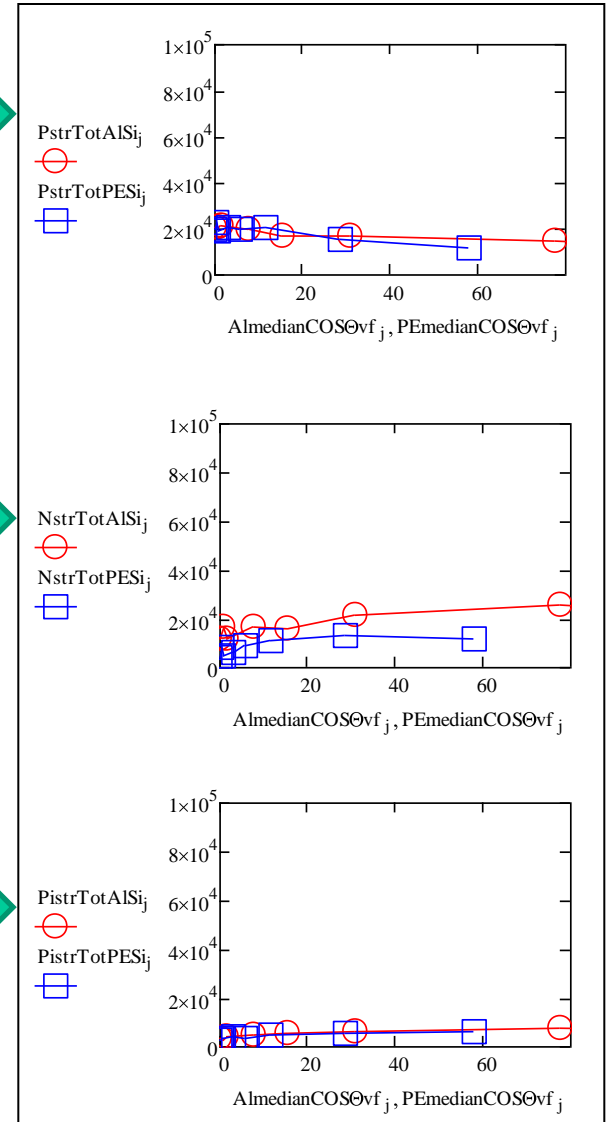


Number of proton induced nuclear reactions per  $\text{cm}^3$  per day (Pstr) vs. median shielding mass, **Al** and **PE**

Number of neutron induced nuclear reactions per  $\text{cm}^3$  per day (Nstr) vs. median shielding mass, **Al** and **PE**

Number of pion induced nuclear reactions per  $\text{cm}^3$  per day (Pistr) vs. median shielding mass, **Al** and **PE**

**Si shells**



## ***Some General Considerations: Plastics and Polymers in the Space Radiation Environment***

- ***Pure generic engineering polymers do not exist – performance properties (including ionizing radiation degradation) depend on the “additive cocktail” and the details of polymer formulation***
  - ◆ *There are hundreds if not thousands of formulations for each generic polymer type; all optimized for particular applications*
  - ◆ *Generic historical ionizing radiation test data are not usually applicable to your polymer formulation for your spacecraft*
- ***The presence of air and oxygen is very important in determining the response of a polymer to ionizing radiation***
  - ◆ *Total Ionizing Dose (TID) leading to property loss can be an order of magnitude lower in the presence of oxygen, at oxygen partial pressures of even a fraction of an atmosphere*
  - ◆ *Possible issue in lightly shielded habitable volumes in long mission duration spacecraft*
- ***Co<sup>60</sup> gamma rays (with or without oxygen) are often used in spacecraft materials testing because:***
  - ◆ *cost and availability are attractive,*
  - ◆ *there is, at present, little compelling evidence driving us to higher fidelity with the flight environment, and*
  - ◆ *There are no surface or deep dielectric charging artifacts as would be expected from any charged particle beam ionizing radiation testing*

# ***Plastics, Polymers, and Adhesives (and Hydrazine)***

<b>Material</b>	<b><u>Bulk</u> (excluding surface damage) limiting Dose in cGy (Co<sup>60</sup> gamma rays in <u>air</u>)</b>	<b>Comments</b>
Multi Layer Insulation Blankets (except Teflon)	$> 10^8$	Verified data (JPL)
Polymeric Materials	$10^7$ to $10^9$	Typical range for contemporary polymer formulations
Adhesives	$10^8$	Typical, usually shielded
Composites, Epoxy	$10^8$	Onset-of-change dose
Composites, Cyanate	$10^9$	Onset-of-change dose
Cabling (Raychem Spec 44/55)*	$5 \times 10^8$	Verified data (JPL)
Seals and Elastomers	$5 \times 10^7$	Usually shielded environment
Lubricants (polymeric)	$10^6$ to $10^9$	Usually shielded environment
Hydrazine (N <sub>2</sub> H <sub>4</sub> )	$10^6$	1% decomposition noted

[http://opfm.jpl.nasa.gov/files/9.2\\_Willis.pdf](http://opfm.jpl.nasa.gov/files/9.2_Willis.pdf)

\* [http://www.gore.com/en\\_xx/products/cables/microwave/radiation\\_resistance.html](http://www.gore.com/en_xx/products/cables/microwave/radiation_resistance.html)

# ***Carbon Fiber Composites***

<b>Material</b>	<b>Bulk limiting Dose in cGy (Co<sup>60</sup> gamma rays in <u>air</u>)</b>	<b>Comments</b>
Composites, Epoxy	10 <sup>8</sup>	Onset of change dose
Composites, Cyanate	10 <sup>9</sup>	Onset of change dose

[http://opfm.jpl.nasa.gov/files/9.2\\_Willis.pdf](http://opfm.jpl.nasa.gov/files/9.2_Willis.pdf)

- ***Carbon fibers have high radiation resistance and mitigate damage to the organic binder phase – Binder phases with more aromatic (i.e. toluene ring like structures in polymer molecules) character have better TID performance***
- ***Conventional epoxy composites generally good to 10<sup>8</sup> cGy***
- ***New cyanate matrix composites (175° C cure) good to 10<sup>9</sup> cGy (highly aromatic binder chemistry)***
- ***Newer 120° C cure cyanates (anti-rad chemical structures) good to >10<sup>10</sup> cGy***
- ***Carbon-carbon composites – no organics so no problem good to >10<sup>10</sup> cGy***
- ***Testing of organic composites is critical areas should be required***

# ***Glasses, Ceramics, and Metals***

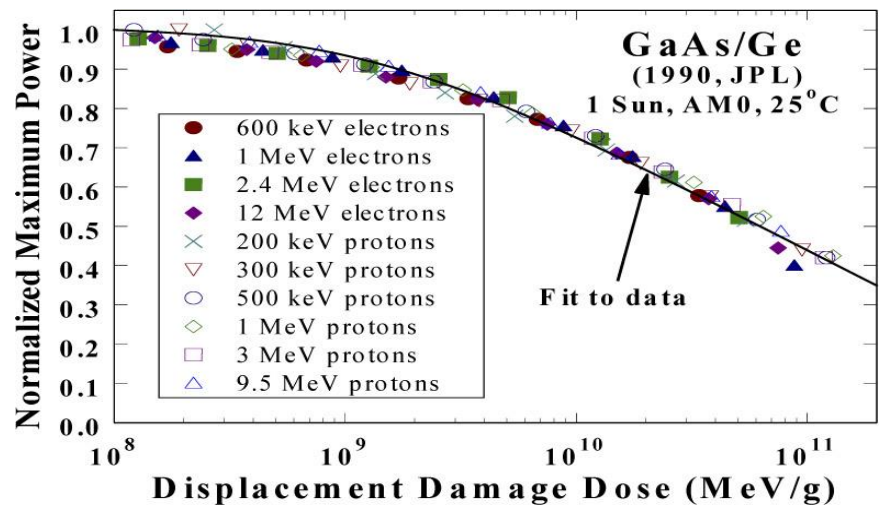
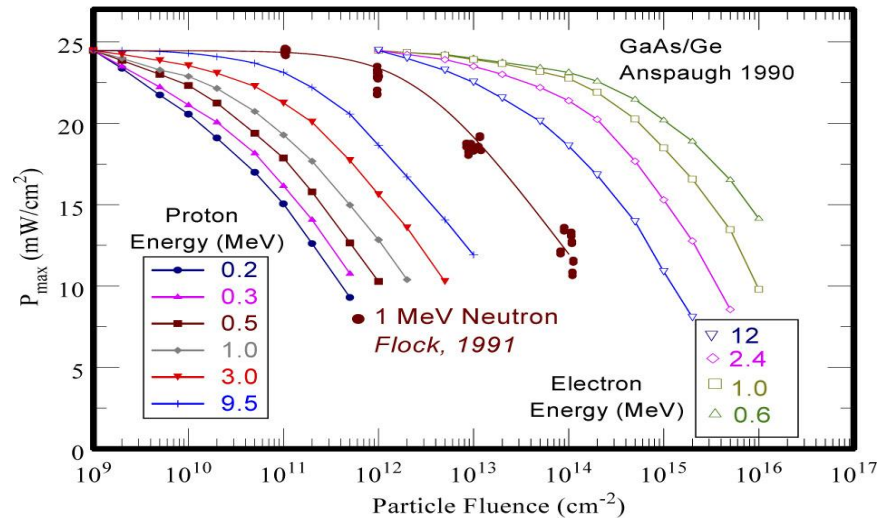
<b>Material</b>	<b>Bulk limiting Dose in cGy (Co<sup>60</sup> gamma rays in <u>air</u>)</b>	<b>Comments</b>
Glasses	10 <sup>5</sup> To 10 <sup>10</sup>	Depends on composition and formulation
Ceramics	10 <sup>12</sup>	Typical Value
Lubricants (inorganic, no polymeric binders)	>10 <sup>10</sup>	Usually shielded environment
Metals	>10 <sup>18</sup>	Typical Value

[http://opfm.jpl.nasa.gov/files/9.2\\_Willis.pdf](http://opfm.jpl.nasa.gov/files/9.2_Willis.pdf)

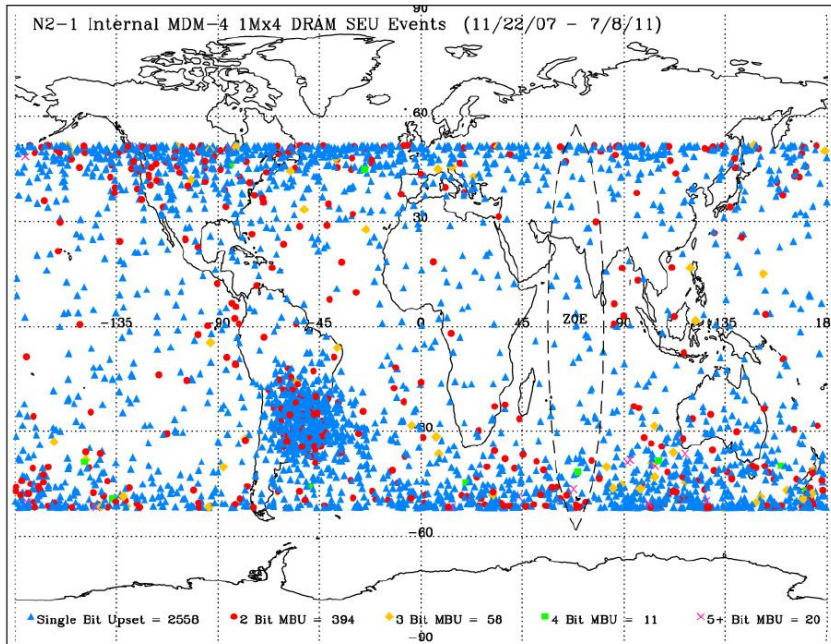
- ***Radiation resistant glasses formulated with cerium oxide for stability***
  - ◆ ***Schott BK-G18, K5G20, LF5G15, SK4G13, SF6G05, etc***
- ***Suprasil III fused silica used in Voyager narrow angle camera***
  - ◆ ***No change after 10<sup>16</sup> cGy 0.8 MeV electrons and 10<sup>8</sup> cGy 2 MeV protons***
- ***Corning 7940***
  - ◆ ***Only minor changes at 10<sup>14</sup> cGy electrons (800 keV), 10<sup>4</sup> cGy 2 MeV protons, and 10<sup>30</sup> neutrons/cm<sup>2</sup>***
- ***Optical Coatings***
  - ◆ ***Surface exposure implies high proton and electron dose and sputtering and surface charging/dielectric breakdown risks***
  - ◆ ***Tantalum oxide and silicon oxide proven in multi-gigarad service on solar cell cover glass in GEO***

# Photovoltaic and Optoelectronic Systems: TID and DDD

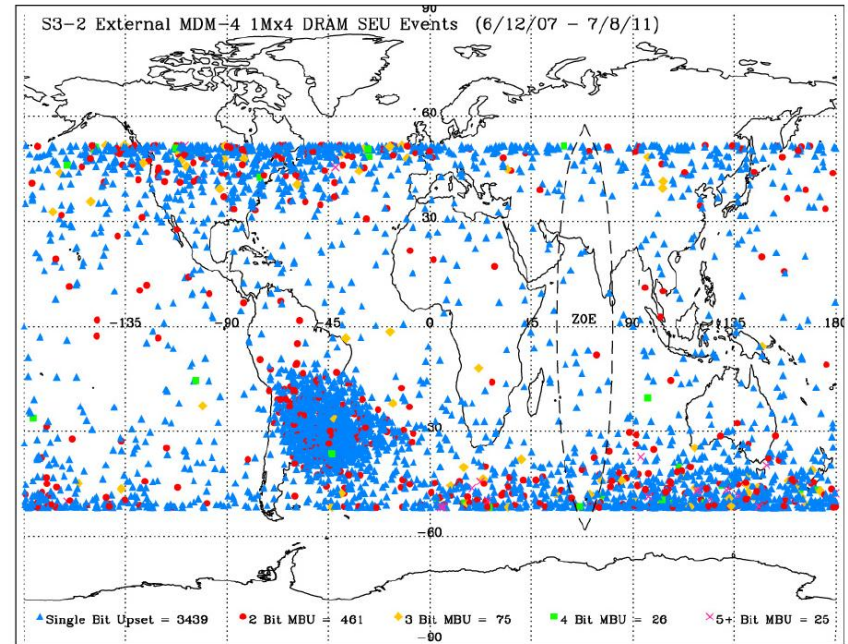
- **Three primary targets for space radiation degradation**
  - ◆ 1) TID Solar cell cover glass darkening
  - ◆ 2) TID Solar cell cover glass adhesive
  - ◆ 3) Displacement Damage Dose (DDD) to the photovoltaic cell itself
- **Items 1 and 2 are largely solved**
  - ◆ Dow Corning, NuSil and Wacker produce suitable DC 93-500 Silicone Adhesives or equivalents that do not darken significantly at  $10^8$  cGy
  - ◆ TID resistant glass solar cell cover glass available from JDSU (ISS) and QIOPTIQ among others
- **DDD resistant space qualified solar cells and complete satellite solar power systems available from:**
  - ◆ Emcore
  - ◆ Azure Space
  - ◆ Boeing
  - ◆ ATK
  - ◆ and others
- **Note that many spacecraft have operated for 15 or more years in geosynchronous orbit without significant power degradation**







Credit: NASA



Credit: NASA

# ***Spacecraft Avionics Systems***

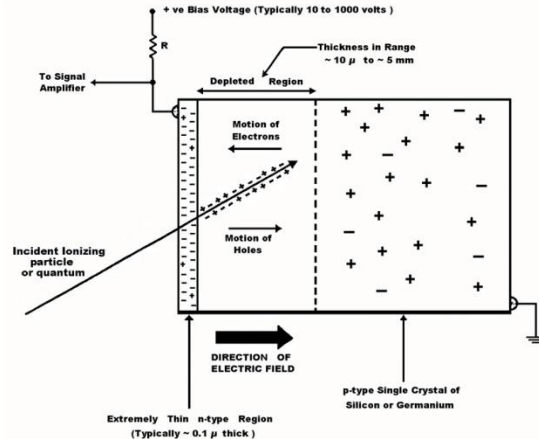


Credit: NASA

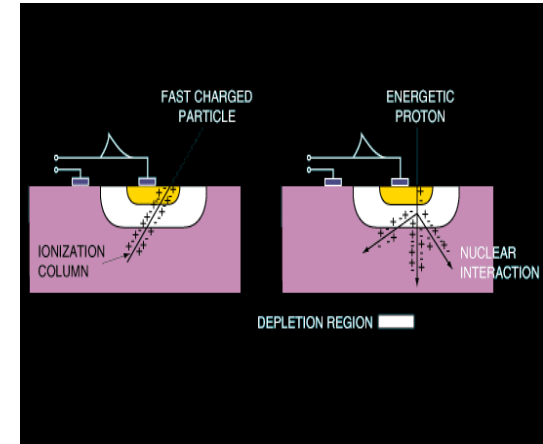
# Cosmic Ray Effects on Contemporary Electronic Technology

## *Solid state electronic devices as charged particle detectors: Single Event Effects (SEE)*

*Schematics of a solid state charged particle detector (right) and a MOSFET transistor (left) illustrating the particle counting or single event upset process. Direct ionization by CR charged particles and charged particles produced by nuclear reactions in the device can produce counts in the detector and SEE events in the transistor only if the devices are powered, i.e. only if an electric field is applied to force charge collection.*



<http://nsspi.tamu.edu/nsep/courses/basic-radiation-detection/semiconductor-detectors>

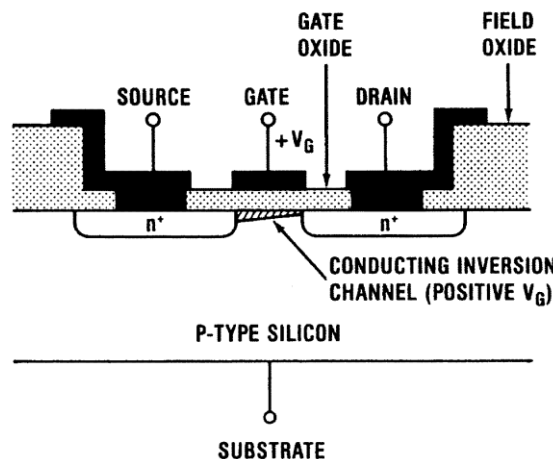


Lauriente, M., Vampola, Al. L., "Spacecraft anomalies due to radiation environment in space," NASA/JAERI 2nd International Workshop on Radiation Effects of Semiconductor Devices for Space Applications, Tokyo, Japan, March 1996.

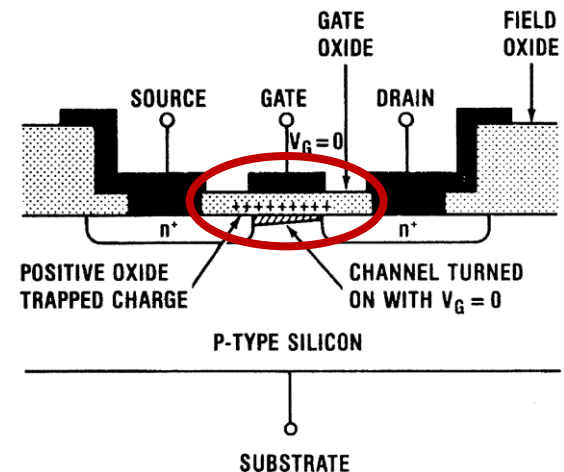
## *Solid state electronic devices as charged particle detectors: Total Ionizing Dose (TID) Effects*

*Schematic of n-channel MOSFET illustrating radiation-induced charging of the gate oxide: (a) normal operation and (b) post-irradiation. The electrostatic field produced by trapped charge in SiO<sub>x</sub> layers changes device characteristics. TID damage accumulated even if the device is unpowered.*

(A) MOS TRANSISTOR — NORMAL OPERATION



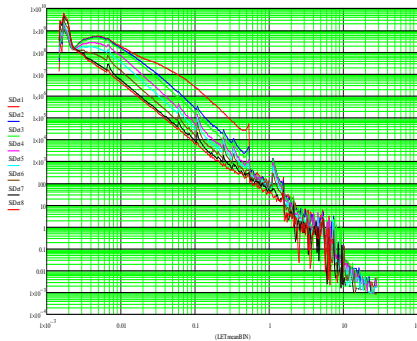
(B) MOS TRANSISTOR — POST IRRADIATION



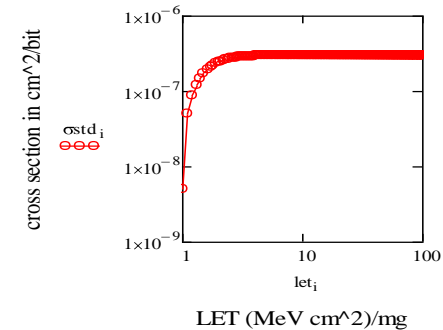
T. R. Oldham, F. B. McLean; "Total Ionizing Dose Effects in MOS Oxides and Devices," IEEE Transactions on Nuclear Science, Vol. 50, No. 3, pp 483-499, June 2003

# Estimating SEE rates: Verifying Spacecraft System Safety and Reliability

Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011



*Single Event Effects caused by direct ionization*



*Differential LET distribution function (spectrum) calculated for the shielding mass distribution function applicable to the electronic device location in the spacecraft*

*Electronic device heavy ion accelerator test data - Measured device cross section ( $\sigma(LET, \Theta, \Phi)$ ) vs. Heavy ion effective LET value expressed as an integral Weibull or the log normal distribution function, or the tabulated test results data*

$$SEU \text{ Rate} = \iiint f(LET) \times \sigma(LET, \Theta, \Phi) d(LET) d(\Theta) d(\Phi)$$

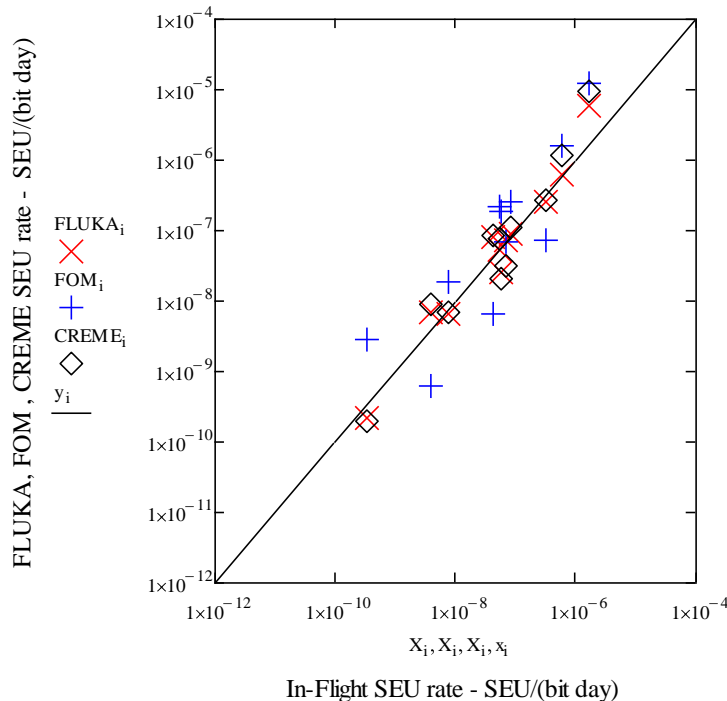
*Single Event Effects caused by in-device nuclear reactions - nuclear reaction recoil fragmentation and spallation products cause direct ionization SEE*

*Nuclear reactions internal to the microelectronic device can be triggered by primary and secondary particle (especially those producing little or no direct ionization e.g. neutrons, protons, and pions) inelastic collisions with microelectronic device nuclei to produce high-LET, short-range fragments.*

$$SEU \text{ Rate} = \sigma(\text{device-particle}) \times \text{Flux (particles/time)}$$

# In-flight vs. calculated spacecraft device SEU rates

Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011



**Shielding Mass Rate Ratio = (10 g/cm<sup>2</sup> Rate) / (40 g/cm<sup>2</sup> Rate)**

Device	Rate Ratio - Flight	Rate Ratio - FLUKA	Rate Ratio - CREME 96	Rate Ratio - FOM
TI (1M x 4) TMS44400	1.2	1.2	3.5	3.7
TI (4M x 4) TI SMJ41640	0.9	1.8	3.4	5.3

***Note that only FLUKA correctly quantifies the shielding mass (i.e. secondary particle shower) effects for the ISS TI CMOS DRAM.***

$$\sum_i \left[ \frac{|X_i - \text{FLUKA}_i|^2}{|X_i|^2} \right]^{0.5} = 5.7 \quad \sum_i \left[ \frac{|X_i - \text{CREME}_i|^2}{|X_i|^2} \right]^{0.5} = 10.6 \quad \sum_i \left[ \frac{|X_i - \text{FOM}_i|^2}{|X_i|^2} \right]^{0.5} = 26.8$$

***Using the same device parameter, the FLUKA based rate calculations show the smallest least squares error and overall acceptable performance compared to CREME-96 and the Peterson FOM, providing some validation for the FLUKA based methods described here.***



# Avionics Systems Safety and Reliability

- *What is the probability of component or box failure?*
  - ◆ *TID and DDD damage buildup over time like a wear-out process leading to failure in a comparatively narrow time interval – Mean Time to Failure*
  - ◆ *SEE is a random (Poisson) process characterized by an average rate and a standard deviation – Mean Time Between Failure*
- *What is the probability of system failure leading to a hazardous condition or loss of mission success?*
  - ◆ *TID and DDD processes can lead to common cause failures of multiple components - so we need margin to make sure this doesn't happen during the mission – **redundancy doesn't really help***
  - ◆ *SEE processes display an environment dependent rate over the life of the mission - the same for day 1 and day 1000 if corrected for environmental variation and not changed by TID/DDD effects – no common cause - Poisson Process - **redundancy helps in a big way***
  - ◆ ***Example – consider a three box redundant system***
    - ✦ *From SEE testing of components and summing the component SEE functional interrupt rates in one box leads to a  $10^{-2}$  /day box level failure probability*
    - ✦ *If all three boxes must fail to fail the system then the daily system failure probability is  $(10^{-2})^3$  /day =  $10^{-6}$  /day*

# Avionics Systems Safety and Reliability

- **Cost –Benefit Trade Space:**

- ◆ **Low initial cost commercial off the shelf (COTS) components and systems**

- ✦ High verification and parts control/auditing cost if used in high reliability (HiRel) systems

- ◆ **High initial cost up-screened or space rated components**

- ✦ Low verification and parts control/auditing cost if used in Hi Rel systems

- **Some commercial sources of HiRel space rated avionics components and systems**

- ◆ <http://www.aeroflex.com/>

- ◆ [http://www.baesystems.com/ProductsServices/bae\\_prod\\_eis\\_rad\\_hr\\_d\\_electronic.html](http://www.baesystems.com/ProductsServices/bae_prod_eis_rad_hr_d_electronic.html)

- ◆ <http://www.maxwell.com/products/microelectronics/about.aspx?sid=MICROELECTRONICS-TECHNOLOGY>

- ◆ <http://www.spacemicro.com/>

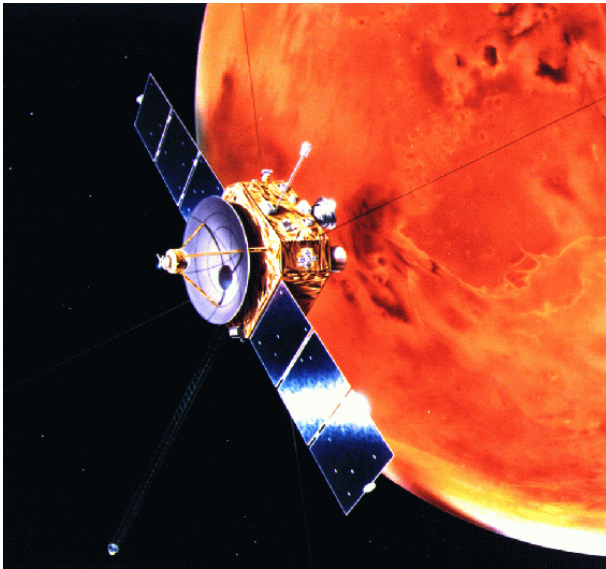




***SO WHAT DO I DO ABOUT ALL THIS?***

# ***What you need to produce a safe and verified design***

- **Well defined design reference mission (DRM) with SEE/TID/DDD environments**
  - ◆ *Mission duration in each SEE/TID/DDD environments*
  - ◆ *SEE/TID/DDD environments definitions for design and verification*
  - ◆ *Mission concept of operations (ConOps)*
- **Space radiation transport/shielding models to allow reasonably accurate TID/SEE/DDD environment calculations (estimates) anywhere in the spacecraft during any phase of the mission**
- **Quantitative spacecraft, subsystem, and component level safety, reliability, and mission success requirements**
  - ◆ *Part, component and box level requirements must be consistent with overall vehicle performance and operations requirements*
  - ◆ *Determines, along with budget marks, parts, component, materials selection and test/verification approach as well as materials/parts control and auditing requirements*
  - ◆ *Determines system redundancy requirements*
- **The trade space**
  - ◆ **Space Qualified materials/parts/systems**
    - ✦ *little or no verification testing and straightforward parts control*
  - ◆ **COTS materials/Parts**
    - ✦ *substantial verification testing and difficult parts control*
  - ◆ ***Note that there is no TID/SEE/DDD acceptance test at this time – That means you must be able to define a qualification test unit or the testing is meaningless => parts control and auditing***
  - ◆ **Are operational hazard controls possible to compensate for the reliability limitations of the final design?**



**NOZOMI**

## ***AND WHAT HAPPENS IF I DO NOTHING?***

*On April 21, 2002 as Nozomi was approaching Earth for the gravity assist maneuver –*

*Powerful “solar flares” (SPEs) damaged the spacecraft's onboard communications and power systems, but the spacecraft was recovered.*

*As the spacecraft approached Mars in 2003 series of intense solar flares damaged a power control circuit (current switch).*

*The subject current switch controlled power to both a telemetry modulator and THE HEATERS FOR THE MAIN PROPULSION FUEL TANKS.*

*What seemed to be an efficient design feature - one switch handles two functions - really exposed the spacecraft to a single point failure*

*Switch failure was unrecoverable after 1000 power cycles*

*Propellant for the main engines freezes solid*

*December 9, 2003 JAXA engineers abandon Mars orbital insertion – adjust orbit to avoid collision with Mars using still operable attitude control jets*

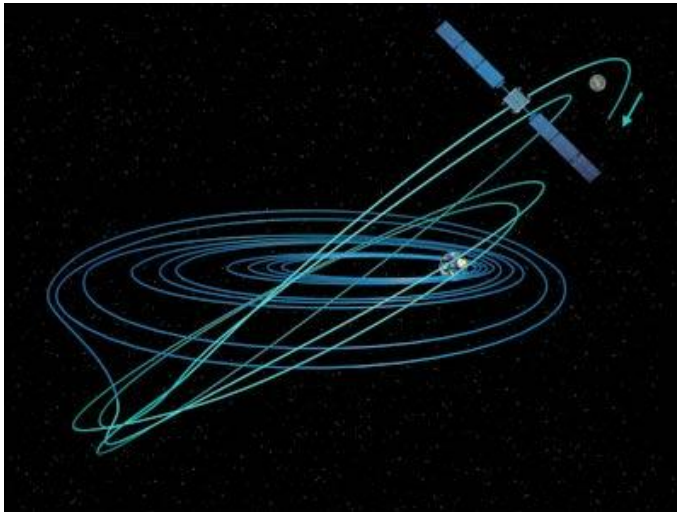
***Dec. 14, 2003 – Nozomi sails past Mars and into oblivion***

**ESA's SMART-1 achieved several firsts.**

- 1) First electric propulsion mission to Moon from Earth**
- 2) Successful demonstration of a mix of commercial off the shelf (COTS) and RAD/SEE hard avionics components in the extreme space radiation environment caused by many passes through the Earth's radiation belts on the way out from the starting geosynchronous transfer orbit (low thrust hall effect ion engines)**
- 3) Demonstrated protection of COTS components from destructive latch-up with circuitry that detects increased current draw from latch-up events and cycles power to clear**
- 4) Demonstration of effectiveness of systems redundancy to support use of COTS hardware**
- 5) Very low cost program ( \$170M with essential 90 % plus mission success)**

### **HOWEVER**

- 1) There were numerous radiation induced anomalies including several electric propulsion system shutdowns and described in O. Camino et al. / Acta Astronautica 61 (2007) 203 – 222.**
- 2) The SMART-1 mission profile was very forgiving of recoverable failures - Just re-point the ion engine and work an new trajectory -**
- 3) Additional work (in progress at ESA) will be needed to make the SMART-1 approach acceptable for safety critical application in manned spacecraft.**



<http://spaceflightnow.com/news/n0410/18smart1/>

***And what happens if I try an unusual approach?***

# ***SUPPORTING MATERIALS***

# *Natural Environment Definitions: CREME 96, Peterson Figure of Merit, and FLUKA Natural Environment Parameters*

- ***CREME 96 and FOM input natural environments for calculations (16)***
  - *GEO/Interplanetary Fluxes, Solar Minimum, Z=1-92*
  - *ISS: 362km/51.6°, Solar Minimum,*
  - *GCR environment based on "A Model of Galactic Cosmic Ray Fluxes", by R.A. Nymmik, M.I. Panasyuk, T.I Pervaja, and A.A. Suslov, Nuclear Tracks and Radiation Measurements, 20, 427-429 (1992)*
- ***FLUKA input natural environments for calculations***
  - *Uses a subset of the CREME-96 Environments as shown below*
    - *H, He, C, O, Mg, Si, Fe, Zn*
    - *Accounts for 90 % + of total GCR flux*
    - *Increases computational speed and efficiency with negligible impact on accuracy*



# FLUKA Methods Overview

- **FLUKA Monte Carlo nuclear reaction and transport code (1)**
  - *Theory driven and benchmarked with data - Based on original and verified microscopic interactions models*
    - *FLUKA is not a tool kit, rather a transport code with fully integrated physics models*
    - *First principle model – no adjustable parameters – does not rely on extrapolated empirical look-up tables*
      - *Nucleus-nucleus interactions from 100 MeV/n to 10000 TeV/n*
      - *Hadron-hadron and hadron-nucleus interactions 0–10000 TeV*
      - *Exact dE/dx ionization (LET) calculation with delta ray production and statistical fluctuations*
      - *No limitation on projectile/target composition or combination*
- **Simple 3D spacecraft model**
  - *Concentric spherical shells – simple shielding mass distribution function for each shell*
    - *10  $\mu$  thick Si “detector” shells at various shielding mass depths – optional 1  $\mu$  metallization layers on outward facing Si shell surface (a generic microelectronic device structure)*
    - *Report TID and nuclear reaction rates for each Si or metallization shell*
    - *Report LET spectra entering outward facing surface of Si detector shell*
- **SEE rate calculations**
  - *Calculate SEE rates with:*
    - *Differential LET spectrum entering each Si detector shell at each shielding depth in the concentric sphere structure (Includes all secondary particle production in “spacecraft shielding mass and metallization layers)*
    - *Directional cross section function,  $\sigma(LET, \Theta, \Phi)$ , from device heavy ion test data*
  - *Same  $\sigma(LET, \Theta, \Phi)$  in CREME-96 and Petersen Figure of Merit (FOM) calculations*

## *FLUKA 2008.3b Calculation Details – Detector Shell Configuration*

- *Spacecraft shielding simulated using FLUKA 3D concentric spherical shells*
- *10 micron Si detector shells are inserted at different shielding depths with optional 11 micron heavy element shells (over-layers) on the silicon shells*
- *Each concentric shell is a FLUKA “region” with specific boundary surfaces.*
- *The volume of the sphere at radii smaller than 5000 cm is treated as a perfect particle absorber in all FLUKA calculations reported here. FLUKA reports the number of particles of LET X entering the 10 $\mu$  Si detector shells per primary particle, as well as the number of nuclear reactions and total energy deposition (TID), also per primary particle, internal to each of the concentric spherical shell shielding shells, 10 $\mu$  Si shells, or 1 $\mu$  metal shells on the Si shells.*

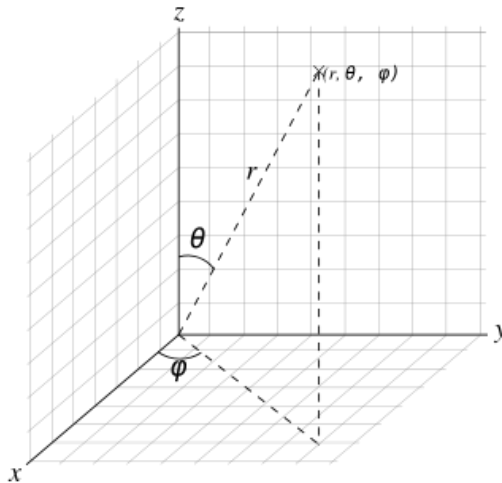
## FLUKA 2008.3b Calculation Details – Detector Shell Shielding Mass

- ***FLUKA launches randomly directed energetic particles into the 3D concentric spherical model spacecraft structure, thereby sampling the full shielding mass distribution function of the model***
  - ***Simulates an isotropic particle flux on a concentric spherical shell structure.***
- ***The shielding mass distribution function metrics (Table 1 below) corresponding to each of the 10 $\mu$  Si detector shells (or 1 $\mu$  over layer shells) are used for data reporting and comparison.***
- ***Example – shielding mass distribution function metrics values in g/cm<sup>2</sup> Al for each Si shell in the concentric spherical spacecraft model. Metrics for another shielding material, X, can be obtained by multiplying the density ratio,  $\rho_x/\rho_{Al}$***

FLUKA Target	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Spherical shell minimum shielding mass thickness (along the radius) in g/cm <sup>2</sup>	0.1	0.5	1.0	5.0	10.0	20.0	50.0	100
Spherical shell median shielding thickness, with geometric cosine correction only, in g/cm <sup>2</sup>	0.14	0.70	1.40	6.90	13.7	27.3	68.1	137.2
Spherical shell median shielding thickness, with cosine and solid angle corrections, in g/cm <sup>2</sup>	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

# FLUKA 2008.3b Calculation Details - Estimating the in-flight SEU rate from the FLUKA LET Spectrum and the Device Heavy Ion Test Data

- **FLUKA simulations produce the differential form of the LET spectra entering each  $10\mu$  Si shell**
  - Forward going particles only reported here – backward going particle fluxes are also calculated, but do not contribute significantly to the result
  - FLUKA “USRYIELD” utility used to recover LET spectra of particles crossing boundaries
  - Results reported on a per geometric region or region boundary and per primary particle basis
  - Scaling to on-orbit primary particle flux/fluence
- **Use the integral form of the microelectronic device directional cross section  $\sigma(LET, \Theta, \Phi)$  and the following  $\sigma(LET, \Theta, \Phi)$  approximations as determined by the test/flight data sources**



**The x y plane is the plane of the microelectronic device die**

- **$\Theta$  and  $\Phi$  define the entry angle of a particle in the microelectronic device coordinate system**
- **$\sigma(LET, \Theta, \Phi)$  represented as a simple geometric solid with a specific aspect ratio (width/thickness)**
  - Isotropic Target, (17)  $\sigma(L, \theta) = \sigma_N(L)$  for all  $\theta$  sometimes observed especially for CMOS DRAM
  - Cosine Law Target, (17),  $\sigma(L, \theta) = |\cos \theta| \sigma_N(L / |\cos \theta|)$  up to  $\theta = 60$  degrees, commonly observed, (17)
  - Right Circular Cylinder (RCC) Target, (18-21). Note that we use the average (first moment) cord length for a given  $\theta$ , not the full chord length distribution
- **The on-orbit rate estimate is then given by:  $Upset\ Rate = \iiint f[LET] \times \sigma(LET, \Theta, \Phi) d(LET) d(\Theta) d(\Phi)$**

## *FLUKA 2008.3b Calculation Details - Estimating the in-flight SEU rate from the FLUKA LET Spectrum and the Device Heavy Ion Test Data*

- ***Estimating Total Ionizing Dose (TID) and nuclear reaction (star) rates per unit volume***
  - ***FLUKA “SCORE” utility reports total ionizing dose and nuclear reactions (“stars”) caused by all:***
    - *Protons*
    - *Neutrons*
    - *Pions*
  - ***SCORE also reports expected in-flight total ionizing dose and “star” density using concentric spherical shell model dimensions and with scaling to on-orbit primary particle flux/fluence values***
- ***How do we know all this works (method validation/success metric)?***
  - ***Calculate least squares error metric –  $\Sigma(\text{in-flight rate} - \text{estimated rate})^2$  as a generic quality assessment of the various SEE rate estimate methods***
  - ***If in flight rate predictions are within “a factor of a few” of the pre-flight predictions the method is usually considered more than adequate for practical work (17)***
  - ***As a minimum, the on-orbit SEE rate calculation method should provide SEE rate estimates accurate to within a factor of 10 at one standard deviation when compared to available in-flight data (22-24)***
- ***Run-to-run variability and error bars in Monte Carlo calculations***
  - ***Monte Carlo models simulate real physical experiments or measurements including natural (random) quantum and statistical fluctuations, so the results of two statistically independent runs are not expected to be equal.***
  - ***As is the case for radioisotope decay, and other Poisson processes, the uncertainty in a Monte Carlo particle or event count is equal to the square root of the number of particles or events in the result***
  - ***In the following, plot symbols are always selected to be larger than or equal to the expected error of the numbers plotted unless two statistically independent FLUKA runs are plotted, in which case the error plot represents the spread in the data points directly***

# ***A FEW KEY REFERENCES***



# ***References***

## ● **Polymeric**

- ◆ <http://www.mddionline.com/article/polymer-materials-selection-radiation-sterilized-products>
- ◆ [http://www-eng.lbl.gov/~dw/projects/DW4219\\_RP\\_Materials\\_Testing/Misc.Stuff/Adhesive%20damage.pdf](http://www-eng.lbl.gov/~dw/projects/DW4219_RP_Materials_Testing/Misc.Stuff/Adhesive%20damage.pdf)
- ◆ <http://www.hitechcontrols.com/cables/technical-information/53-fluorinated-polymeric.html>
- ◆ <http://www.dunmore.com/industries/aerospace.html>
- ◆ <http://www.sheldahl.com/Product/index.htm>
- ◆ [http://www.gore.com/en\\_xx/products/cables/microwave/radiation\\_resistance.html](http://www.gore.com/en_xx/products/cables/microwave/radiation_resistance.html)
- ◆ <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/18396/1/99-1875.pdf>
- ◆ [http://opfm.jpl.nasa.gov/files/9.2\\_Willis.pdf](http://opfm.jpl.nasa.gov/files/9.2_Willis.pdf)

## ● **Space Photovoltaics**

- ◆ <http://gltrs.grc.nasa.gov/reports/2007/CP-2007-214494.pdf>
- ◆ [http://www.jdsu.com/ProductLiterature/sccrrg\\_ds\\_co\\_ae.pdf](http://www.jdsu.com/ProductLiterature/sccrrg_ds_co_ae.pdf)
- ◆ <http://www.qioptiq.com/space.html>
- ◆ [http://www.wacker.com/cms/media/publications/downloads/6427\\_EN.pdf](http://www.wacker.com/cms/media/publications/downloads/6427_EN.pdf)
- ◆ <http://www.ellsworth.com/display/productdetail.html?productid=2070&Tab=Vendors>
- ◆ <http://www.ellsworth.com/display/productdetail.html?productid=2396>
- ◆ <http://www.nusil.com/products/engineering/index.aspx>

## ● **SEE/TID/DDD Test Data on EEE Parts and Assemblies**

- ◆ <http://radhome.gsfc.nasa.gov/radhome/RadDataBase/RadDataBase.html>
- ◆ <http://radcentral.jpl.nasa.gov/>
- ◆ <http://www.astm.org/Standards/F1892.html>
- ◆ <http://www.aero.org/publications/crosslink/summer2003/05.html>
- ◆ <http://snebulos.mit.edu/projects/reference/NASA-Generic/JPL-00-06.pdf>

## ● **Standards**

- ◆ **SMC Standard SMC-S-010 (DoD; Most recent revision)**
- ◆ **SMC Standard SMC-S-016 (DoD; Most recent revision)**
- ◆ **JSC-8080 (Most recent revision)**

# ***References***

## ● **Spacecraft Experience**

- ◆ Octavio Caminoa, Maria Alonsob, Daniel Gestalc, Jurriaan de Bruind, Peter Rathsmanc,, Joakim Kugelberge, Per Bodine, Sascha Rickenc, Rick Blakeb, Pablo Pardo Vossd, Luca Stagnarof; “SMART-1 operations experience and lessons learnt,” *Acta Astronautica* 61 (2007) 203 – 222
- ◆ A. Elfving, L. Stagnaro, A. Winton; “SMART-1: key technologies and autonomy implementations,” *Acta Astronautica* 52 (2003) 475 – 486
- ◆ Steve Koontz, Paul Boeder, Courtney Pankop, Brandon Reddell; “The Ionizing Radiation Environment on the International Space Station: Performance vs. Expectations for Avionics and Materials,” *Proceedings of the IEEE NSREC 2005 Conference, Radiation Effects Data Workshop, Paper W-17, Seattle, Washington, USA.*
- ◆ Steven L. Koontz, Mike Pedley, Ronald R. Mikatarian, John Golden, Paul Boeder, John Kern, Hagop Barsamian, Joe Minow, Richard Aststatt, Mary J. Lorenz, Brian Mayeux, John Alred, Carlos Soares, Eric Christiansen, Todd Schneider, and Dave Edwards; “Materials Interactions with the Space Environment,” PP 44-56, in Protection of Materials from the Space Environment, ICPMSE-6, Jacob I. Kleiman and Zelina Iskanderova Eds. Kluwer Academic Publishers, Dordrecht, London, Boston, 2003
- ◆ Steven Koontz, Brandon Reddell, Paul Boeder; “Calculating Spacecraft Single Event Environments with FLUKA,” *Proceedings of the IEEE NSREC 2011 Conference, Radiation Effects Data Workshop, Paper W-33, Las Vegas, Nevada, USA, July 25-29, 2011*

## ● **NASA Electronics Parts and Packaging Program**

- ◆ <https://nepp.nasa.gov/>

## ● **NASA JPL**

- ◆ [http://parts.jpl.nasa.gov/docs/Radcrs\\_Final.pdf](http://parts.jpl.nasa.gov/docs/Radcrs_Final.pdf)
- ◆ <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/40790/1/08-13.pdf>
- ◆ <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/21928/1/97-0350.pdf>

## ● **IEEE Transactions on Nuclear Science**

- ◆ <http://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=23>

## ● **NASA Space Radiation Program (Human Health Effects)**

- ◆ <http://spaceradiation.usra.edu/about/>